

AEROVEHICLES FOR PLANETARY EXPLORATION

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Planetary Aerobots are an innovative, new type of lightweight and low-cost telerobot, one which can fly and navigate in a dynamic 3-dimensional atmospheric environment. JPL has recently discovered and demonstrated a balloon buoyancy control concept which is applicable to several planets. This altitude control concept employs phase change fluids such that a planet's atmosphere is used as a giant heat engine to provide the mobility energy to ascend and descend at will. There are potential flight experiment opportunities as early as 1999 for Venus, 2001 for Mars and 2000-04 Titan. Telerobotics technology enables the acquisition of surface and atmospheric science at multiple sites designated by scientists and mission designers. There are challenging technical problems in vehicle mobility, on-board perception, and autonomous control and navigation. Technology in these areas will be demonstrated in a series of gradually more ambitious terrestrial flights. There are also concurrent terrestrial applications to global climate and pollution studies as well as to autonomous ocean exploration.

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1.0 INTRODUCTION

The exploration of the solar system has proceeded in several phases beginning with flyby missions, proceeding to orbiters, then to probes and landers and finally mobile vehicles that operate on the surface and in its atmosphere. For the most accessible planetary bodies, Venus and Mercury, we are now entering the phase of mobile exploration of the surface and atmosphere. This paper is concerned with the use of robotically-controlled and autonomous aerovehicles- aerobots - and their use in planetary exploration,

The earliest solar system exploration missions were flyby missions which made no attempt to orbit or land on the targeted object. Typically, flyby missions conduct observations for a few days around closest approach. Later, using more sophisticated technology, orbiter missions were developed which observed the planet for months or years from close range, acquiring detailed maps of the surface and characterizing diurnal and seasonal variations in any atmosphere. To date, orbital missions have been carried out only for the Moon, Mars and Venus.

In this same time frame, atmospheric probes and surface landers have conducted much closer range observations. Landers have now been placed on the surfaces of the Moon, Mars and Venus and obtained images and geochemical and atmospheric data of the immediate regions of landing sites. In the early 1970s, during the Apollo program, mobile surface exploration began when the U.S.A. deployed rovers to the lunar surface which were used by the astronauts. In the same time period, the Soviet Union carried out unmanned rover missions to the lunar surface. To date, no rover mission has been successfully carried out to any other body than the Moon, although the U.S.A. currently has firm plans to launch a Microrover Flight Experiment (MFEX) to Mars as part of the Mars Pathfinder mission. In addition, Russia is developing its own Mars rover, Marsokhod, which will fly to Mars, but at a later date.

Mobile atmospheric exploration of the planets is in some respects ahead of mobile surface exploration. In 1985, the Soviet Vega mission successfully deployed two balloons into the upper atmosphere of Venus. A Soviet-French-American experiment tracked these balloons for two days on the side of the planet visible from Earth at an altitude of 54km determining wind velocities and characterizing atmospheric turbulence. A French-Russian team is currently working on the development of a balloon mission for the 1998 launch opportunity to Mars. This experiment will be equipped with imaging cameras and meteorological and geochemical sensors. It is designed to operate in the lower atmosphere of Mars and make excursions to the surface during the night.

At JPL, we are now involved in planning and developing the technology for the next phase of planetary exploration using buoyant vehicles. This phase will draw on the technical experience of earlier missions but will employ telerobotic and autonomy technologies to control motion in all three dimensions. There are significant parallels in these systems to the capabilities needed for mobile surface vehicles. However, there are also significant new challenges in atmospheric exploration which demand distinctly different approaches.

The original motivation for developing a new class of robotically controlled balloon or aerovehicle - hereafter referred to as aerobot was to advance the exploration of Venus. Following the exploration of the surface of Venus by short lived Soviet landers and by the Vega balloons, the U.S.A. carried out the Magellan mission which mapped the surface of Venus using radar sensors. The radar revealed a surface with a great variety of structural and volcanic features. There has been no clear pathway, however, to follow up the Magellan mission with a long-lived in situ mission.

Venus, Earth's estranged sister planet, has a dense atmosphere exceeding 92 bars in pressure and surface temperatures in excess of 470C. Its surface is obscured from view at visible wavelengths by high altitude haze and clouds as well as the molecular scattering of the clear atmosphere beneath. The Soviet Venera landers functioned for less than two hours on the surface. With advanced thermal techniques and the use of vacuum insulation, it may be possible to extend surface lifetime to 1-2- weeks. Much longer lived systems, however, will require radioisotopic power and temperature control systems which will be costly, expensive and present environmental concerns. Rovers appear even less practical and have not been the subject of serious study.

An aerobot on the other hand can turn the environmental challenges of Venus to advantage. The Venus Flyer Robot, conceived at JPL in 1993, would make brief excursions to the hot surface environment of Venus to acquire data and return to the cooler, higher altitudes to telemeter those data to an orbiting relay station or directly to earth. This concept drew on the principles of lightweight and low power controls and instruments used in the microrover systems also developed at JPL and used in the MFEX/Pathfinder mission. However, in the case of the Venus aerobot, these attributes were even more important.

The need for a lightweight payload and control system on an aerobot is obvious. The need for low power is also apparent but for Venus exploration it has a significant new dimension. The lifetime of a thermally insulated gondola in the Venus lower atmosphere is limited not only by parasitic heat leaks from the environment but also by power dissipated in the electronics. The power required for information acquisition systems can still be reduced substantially. The power for communications systems is beginning to approach theoretical limits and must be much larger. Hence a strategy of acquiring data near the surface and telemetering it from a higher altitude makes practical sense.

While the original motivation for the aerobot was for Venus exploration, these vehicles are becoming recognized as powerful tools for exploration of all planets with substantial atmospheres. Current missions such as Galileo and Cassini rely on short-lived entry probes which sample only one location and return a burst of data as they sink into the atmosphere. Aerobots represent the same kind of advance in exploration potential over single-shot entry probes that Planetary orbiters bear to planetary flyby spacecraft. Planetary aerobots are engaging mission concepts which will capture the imagination of the public in their ability to explore hitherto inaccessible regions of our Solar System [1].

We will discuss the opportunities for using telerobotic control of free-flying balloon aerovehicles or "aerobots" in planetary atmospheres, capable of vertical mobility in atmospheres using altitude control systems. We will also examine the use of prevailing wind patterns to enable global exploration. We will also consider the challenges of precision landing of aerobots. Emphasis is placed on approaches to autonomous navigation for achieving desired latitudes and longitudes in planetary atmospheres using on-board flight dynamic models and a combination of real-time sensory perception (surface topography, balloon state and atmospheric conditions) and periodic independent position updates.

The design of a planetary aerobot testbed vehicle is described which will conduct a series of terrestrial technology demonstrations which: 1) move gradually from manual teleoperated control of the robotic vehicle to fully autonomous altitude change at-id landings; 2) achieve increasingly long-range mobility from widely separated launch and landing sites (first predicted sites followed by designated sites). The missions that may use this technology include both scientifically motivated missions and technology demonstration opportunities. They include Venus 1999 or 2001, Mars 2001, Titan 2000-04.

II MISSION OPPORTUNITIES

There are opportunities for using aerobot technology at Venus, Mars, and Titan the Outer Planets as well as terrestrial applications of the technology. In selecting planetary mission opportunities, an important consideration is the availability of a high performance telecommunications link between the planet and earth. While communications directly from the aerobot is possible and was, in fact, conducted from the Vega missions in 1985, the performance is greatly enhanced when a large steerable antenna, which can only be practically deployed from a spacecraft, is available to the aerobot for relaying data.

A. VENUS

The Vega-1 and Vega-2 balloons deployed in 1985 (2,3) were entirely passive vehicles which operated at a constant altitude of 54 km for about 2 days before radio contact was lost when the batteries failed. Concepts have been developed for operation over the entire depth of the Venus atmosphere taking advantage of reversible fluid balloon systems. A Venus aerobot could sample the surface and near surface atmosphere at various landing sites by means of global maneuverability (in both altitude and position) and by use of autonomous navigation.

1. Balloon Experiment at Venus (BEV): An inexpensive flight demonstration called Balloon Experiment at Venus (BEV) has been designed as a piggyback to a possible 1999 or 2001 NASA Discovery Mission. Discovery is a new NASA program of moderate-cost solar system exploration missions. The BEV flight demonstration would refine on-board navigation designs, by characterizing the robotic vehicle and on-board sensor operation. It would relay data acquired with a mapping sensor to a deployment vehicle which would communicate these data to earth.

2. **Venus Flyer Robot:** A much more sophisticated system taking advantage of advances in autonomy would realize the goal of repeated observations of the Venus surface without the use of radioisotopic power sources. To fully exploit these systems a relay orbiter would be needed.

B. MARS.

Simple uncontrolled Mars balloons have been proposed by a joint Russian/French team as noted above and by a NASA Discovery Mission proposer [4,5]. The Mars 9\$ balloon system as conceived in January 1995, will fly above the surface for most of the mission taking pictures. It will initiate a high risk descent to the surface only at the end of its less than 10 day life for an important microwave sounding experiment in search of subsurface water. High surface wind velocities expected during the 1998 Northern winter season, will make these surface measurements quite hazardous if not impossible. It will relay data to one of the Mars Surveyor orbiters which are now being planned by the U.S.A.

Future Mars aerobots, which could fly as early as 2001, will incorporate vertical mobility subsystems to enable landings, navigation sensors to estimate position and velocity (and thus wind speeds), and on-board flight dynamic models to achieve autonomous navigation.

Reversible fluid altitude control systems such as those recently developed for Venus, which depend on a pronounced temperature gradient with height in the atmosphere, will not operate in the thin atmosphere of Mars which is nearly isothermal. However, concepts have been developed which will permit extended operations. Long-duration Mars aerobot missions will be able to survey much of the Martian surface and map available subsurface water resources if they exist.

C. TITAN.

Titan is the large moon of Saturn and the only satellite in the solar system with a substantial atmosphere. This is primarily nitrogen. A Titan aerobot equipped with a reversible fluid buoyancy control system would be able to safely and repeatedly explore the ice continents and possible methane oceans below the perpetual haze layers, recently revealed by the Hubble Space Telescope IR observations. Titan's atmosphere provides an excellent opportunity for a reversible fluid balloon system similar in concept to Venus although using much different fluids.

The availability of a communications orbiter for missions at the distance of Saturn is critical for a viable aerobot mission. The 1997 launched Cassini mission offers an opportunity for a low cost technology demonstration using the available Titan Probe communications link. Cassini will be in Saturn orbit beginning in 2004 to at least 2008. Frequent Titan flybys are planned which enable a possible relay from a Titan aerobot to the Earth through the Cassini spacecraft. A small Titan aerobot could be launched in 2000 on a short trajectory timed to arrive at Saturn about the same time as Cassini. Similar aerobot technologies apply to other planets and satellites with deep atmospheres, such as Jupiter, Saturn, Neptune, and Uranus.

D. TERRESTRIAL APPLICATIONS

Temperature and pressure characteristics of the Venus upper-atmosphere and the Earth's lower-atmosphere are very similar. This makes aerobots designed for the Venus upper-atmosphere viable for environmental, climatological, reconnaissance and communications applications on the Earth. Preliminary studies have begun to examine the potential of reversible fluid balloon systems for exploring the nature of and the hazard to aviation of dust plumes of active volcanoes, primarily along the Pacific rim, that endanger air travel between North America and Asia. Such vehicles could carry pollution sensors and sound the lower atmosphere repeatedly on cycles of a few hours or less. Vehicles could also operate in the region just below the tropopause (10 -20 km) and make repeated measurements of such atmospheric gases as water vapor. This will allow better understanding of the stratospheric energy balance, which is important to climate studies. Multiple, altitude-varying balloons would also be useful to study the global Earth atmosphere structure.

E. PARALLELS TO DEEP SEA EXPLORATION

Parallels to the challenges addressed here and opportunities for technology exchange exist with deep sea robotics. Relevant technologies to both atmospheric and deep sea environments include: global autonomous navigation in uncertain environments; embedded 3-dimensional world models of a fluid dynamic media governed by buoyancy and directional and random currents; on-board sensor data processing for position determination; and surface terrain matching algorithms for achieving desired exploration sites.

HI TECHNICAL APPROACH

Here we describe the closed-system reversible-fluid buoyancy control approach in more detail, review a series of Earth demonstrations of the technology that were conducted at JPL during the last year and describe how altitude control can be used to provide aerobot lateral mobility.

A. Buoyancy Control using reversible fluids

Aerobots designed for long term operation in planetary atmospheres require methods of altitude control that are both energy efficient and involve minimal expenditure of consumables. A closed-system, reversible-fluid balloon, uses the atmospheric temperature difference as a function of altitude as a heat engine to provide the motive power to change altitude. This type of system was originally proposed by Moskalkenko in Russia and has been refined recently by JPL (6). The JPL system meets the above aerobot criteria and is applicable to exploration of Venus, Titan and the outer planets.

A reversible fluid is either a gas or a liquid, depending on pressure and temperature. It is this phase change which can be used to control the buoyancy of a balloon system. When the reversible fluid is in the gas phase, the balloon has a lower average density than the surrounding atmosphere thus providing a net increase in lift. Conversely, when the fluid is in the liquid phase, the balloon has a higher average density than the surrounding atmosphere thus providing a negative lift.

The choice of reversible fluid determines the equilibrium altitude about which the balloon system oscillates indefinitely. In the hot atmosphere of Venus, a combination of water, which is a liquid at room temperature, and ammonia which is normally a gas at room temperature, can be used as reversible fluids for operation over a significant range of atmospheric altitudes. In the cold atmosphere of Titan the inert gas argon is suitable. Although use of a single gas, less dense than the ambient atmosphere, is simplest, the use of a dual gas system provides more flexibility in the design of the system. For example, a primary balloon filled with the light gases helium or hydrogen can be combined with a balloon filled with a dense reversible fluid such as Freon R114 in a reversible fluid balloon that will function in the earth's atmosphere and also potentially on Venus. Single-balloon concepts using fluid mixtures are also feasible.

A purely passive system such as that described above will continue to oscillate about an equilibrium altitude. However, if the liquid is sealed in a pressure vessel before the balloon drops below this equilibrium altitude, the balloon will descend to the surface or deep into the planetary atmosphere. The balloon will return to the equilibrium altitudes as the liquid is evaporated and allowed to reinflate the secondary balloon. In the case of Venus, this allows the sensor payload to be re-tooled and for data communications to take place under the most favorable environmental conditions of the high, cool equilibrium altitude. Figure 1 illustrates the concept of reversible fluid balloon altitude control.

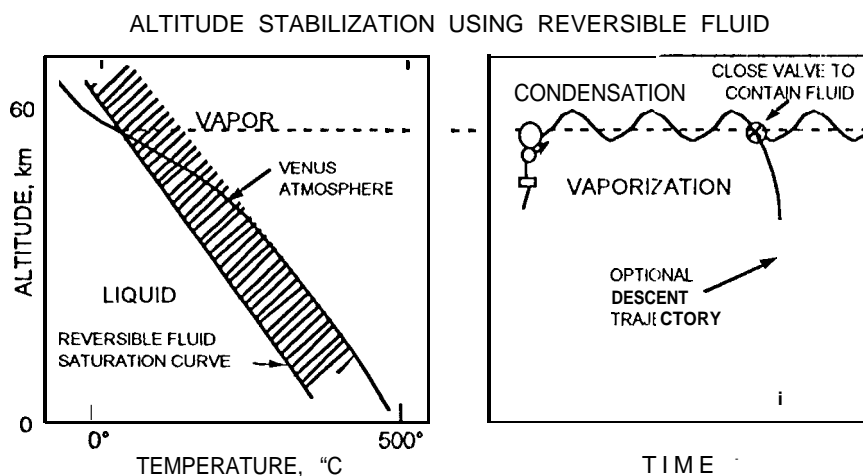


Figure 1: Venus Balloon Equilibrium Altitude and Cyclic Motion

Because the atmosphere of Mars is similar to Earth's stratosphere and has a more uniform temperature above about 2 km altitude, reversible fluid buoyancy control technology does not work. Alternate buoyancy control schemes have been identified including superpressure balloons, chemical interactions with the CO₂ atmosphere to produce ballast, hot air balloons, and secondary balloons using periodic buoyancy gas replenishment from reservoirs and gas release and balloon deflation. Such systems may be demonstrated in the near future depending on programmatic opportunities.

C. Using Altitude Control to Achieve Lateral Mobility:

By controlling vertical mobility, aerobots can select altitudes where wind speeds and directions provide them a wide range of horizontal mobility. This is especially true at Mars and Venus where rich altitude-variable wind gradients enable near global planetary access. Soft landing of the science payloads on planet surfaces is achieved by means of a flexible and possibly robotic landing "snake" tethered below the vehicle. Robotic snake concepts have been proposed for Venus which use ambient atmosphere in a pneumatic control system to achieve desired articulation. As the snake contacts the surface, it relieves the vehicle of some of its gravity load. This enables the vehicle to "hover" at a fixed distance away from the surface without impacting it.

IV. ROLE OF TELEROBOTIC TECHNOLOGIES

To exploit the techniques of altitude control for aerorobot exploration it is necessary to develop and demonstrate telerobotic technologies in lightweight low power systems. These technologies for aerobots build on the prototype balloon vehicles described above and on the current NASA scientific ballooning technology program [7, 8]. Specific technology areas include:

Planetary Atmosphere Autonomous Navigation: Systems will be needed to perform 3-D navigation and execute maneuvers to achieve long autonomous flights, including periods when the aerobot is not in communications with the earth. Research is needed to address global navigability at planetary scales to various target site sets, as well as local navigability to terminally guide the aerobot to a specific target of opportunity within the set. Engineering models of the planetary atmosphere weather patterns must be developed, focusing on relatively simple computer models (8) for on-board autonomous navigation combined with periodic Earth or orbiter spacecraft updates.

On-Board Sensors and Perception: Sensing options for vehicle navigation over surfaces may include terrain profile sensors that match terrain profiles against previous mission topographic data; sun or star sensors for latitude determination; inertial systems for dead-reckoning navigation and gondola orientation; and terminal sensing using vision-based correlation methods.

Vertical Vehicle Mobility Mechanisms: Vertical vehicle mobility concepts for reversible fluid balloons include activation of valves that control the rate of fluid boil-off and condensation. Advanced concepts that could be researched later include tethered dual balloon/kites, blimps etc. for increased maneuverability. Vertical mobility concepts for Mars need to be studied and promising options chosen for further research and technology demonstrations,

A. Planetary Aerobot Testbed Vehicle

An aerobot test vehicle has been designed to carry out a proof of concept of these technologies. Figure 3 shows the proposed terrestrial demonstration aerobot testbed vehicle architecture. The vehicle will be designed and constructed and used in Earth flights to test and demonstrate telerobotic technologies.

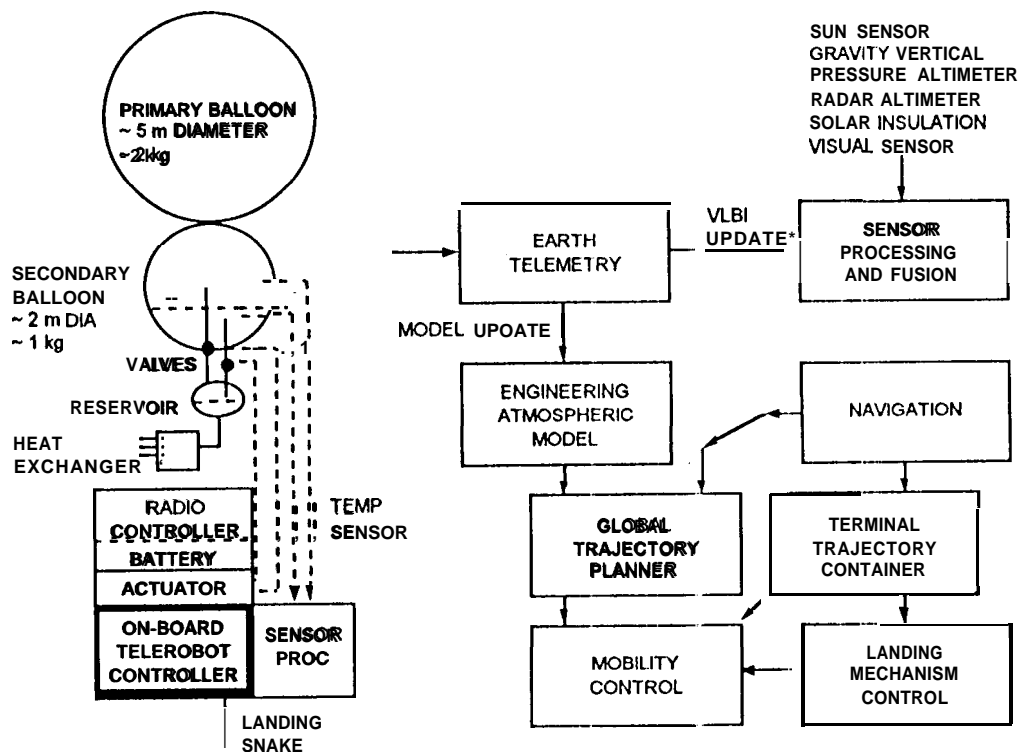


Figure 3: Planetary Aerobot Testbed Vehicle System

The Planetary **Aerobot** Testbed Vehicle uses two attached balloons. Helium in one balloon provides most of the buoyancy. A second, smaller balloon provides altitude control by using a “reversible fluid” condensing at a particular pressure and temperature. Several reversible fluids are possible for use at Earth, each with a different condensation equilibrium altitude. Freon R114, with a condensation altitude of 5-7 km, depending on season, is a suitable fluid. With an appropriate amount of reversible fluid, the vehicle cruises at the equilibrium altitude. However, heat transfer time lags cause a limit-cycle oscillation with an amplitude of 1-2 kilometers about the equilibrium altitude.

To descend, the liquid condensing in the cold upper half of the cycle is trapped inside a small pressure vessel thus creating negative lift. The system then descends into warmer lower altitudes, and eventually settles on the surface. A landing “snake” keeps the gondola hovering off the surface. At any point in a descent, valves can be opened to allow the now super-heated liquid to boil and **re-inflate** the small, buoyancy-control balloon. With a net positive lift, the system goes up to the cooler upper altitudes and resumes oscillation about the equilibrium altitude. It is this vertical control, combined with a varied and rich wind-structure, that can enable long term, cyclic operations to and from landing sites at Earth.

The entire **testbed** mass is expected to be 15-25 kg depending on the degree of autonomy incorporated and the efficiency of the heat exchanger system. The gondola system includes a **teleoperated** or autonomous controller, flight telemetry subsystem, Global Positioning System (GPS) receiver, satellite communications subsystem, Federal Aviation Administration (FAA) transponder, redundant balloon cut-down subsystem controller, structure/insulation and batteries. The reversible fluid heat exchanger system includes valves, actuators, heat exchanger fins, a reservoir and plumbing.

Testing of this vehicle will exploit the fact that the Earth’s troposphere between 0 to 6 km has similar temperature-vs-pressure gradients as the Venus atmosphere at 55-60 km.

B. Robotic Control Architecture

The control architecture for the testbed is designed to eventually enable autonomous navigation and maneuverability. Table 1 compares the control architecture of a rover (JPL’s Pathfinder **Microrover**) with a Planetary Aerobot.

Uncontrolled descent only lands the vehicle somewhere along its wind-driven path. Controlling the descent rate allows the target to be achieved, provided wind and thermodynamic profiles are nominal and the descent start corridor is chosen correctly. The nominal descent rate is matched with the expected horizontal wind velocity, so as to land at the required target. A more advanced approach uses on-board sensors to iteratively estimate the likeliest landing point, and continually adjusts the descent rate to guide the vehicle to the prescribed site. This increases the reliability with which the target along the wind-driven path is achieved, but increases system complexity. Controlled descent is particularly challenging with reversible fluid altitude control since the mobility mechanism available to the robot as it goes down is one-sided. The descent rate can only be made slower and not faster. Augmentation of reversible fluid altitude control with variable geometry surfaces to increase descent rate has been considered and will be further examined.

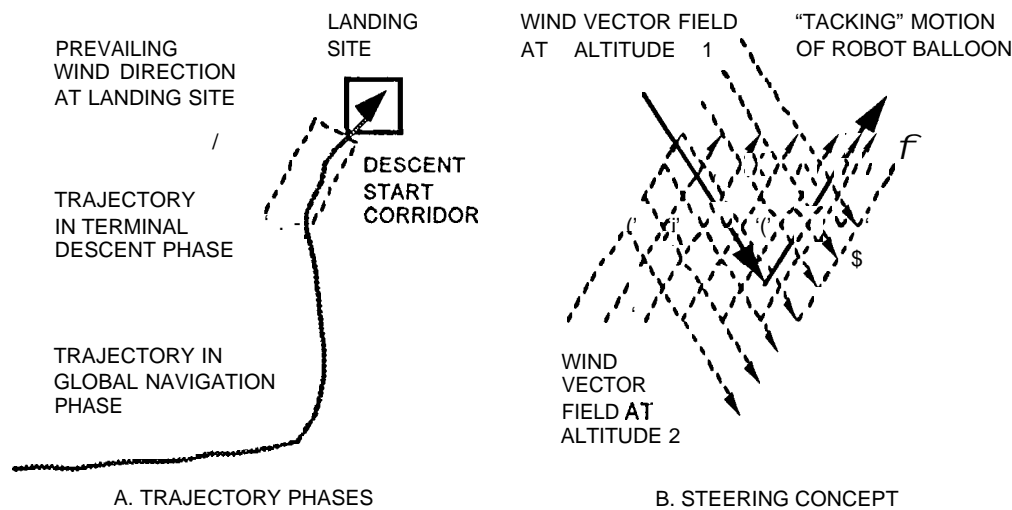


Figure 4: Venus Robot Trajectory and Steering Concepts

The goal in the global navigation phase is to maneuver the aerobot from its initial 3-D atmospheric location to an approach position where landing operations can begin. Periodic command and navigation updates will be required. For planetary aerobots, communications are possible only when the aerobot is on the nearside of the planet unless an orbital relay satellite is used. For Venus this occurs for a period of 3-4 days during every 6-8-day orbit while in the upper atmosphere winds (at 50-60 km altitude). Supervisory control operations, mixing human commands with on-board autonomy, are therefore anticipated.

Global navigation of an aerobot is analogous to a microrover navigating inaccurately modeled static terrain, although it is much more challenging, because the wind environment is dynamic and 3-dimensional. The traditional robotics problem of going from Point A to Point B, which by now is almost trivial in conventional robots, is very difficult in atmospheric robot navigation. Moving from one location to another will involve changing altitude to exploit one or more wind-vector directions as illustrated in Figure 4B.

The aerobot uses a simple on-board wind pattern model for trajectory generation. This wind model is analogous to the world-model embedded in a conventional robot to map obstacles. An aerobot's wind pattern model captures planetary wind behavior in terms of prevailing wind directions, wind velocities vector directions as a function of altitude, vertical down/up draft, cloud-cover, and day/night insolation models. These comprise relatively simple computer models Suitable for on-board use and are not complex meteorological models.

Data from prior planetary missions , e.g. Venus [3] provides a start for such models. For example, the Vega balloon experiments explored the Venus middle cloud layer at 50-55 km altitude. Vertical winds are large (3 m/sec) and variable, with turbulent episodes lasting about an hour. West to East average zonal winds of about 69.4 m/s for Vega 1 and 66.0 m/s for Vega 2 were detected. Both Vega balloons drifted about 11000 km from the local midnight meridian into the late morning sky, carried by strong, predominantly zonal East-West winds. Vega 1 initially encountered weak southward winds, which changed to northward winds later in the missions. These meridional winds produced north-south displacements in the Vega 1 trajectory that never exceeded 50 km. The Vega 2 meridional winds were consistent y northward with a mean velocity near 2.5 m/s which produced more than 400 km of displacement toward the north pole.

Challenging maneuvers include long longitudinal traverse, equator crossing, and latitude change. There will initially be large uncertainties in global navigation. Early efforts will therefore focus on reaching regions of fairly large size, or of reaching targets of opportunity, instead of trying to achieve pin-point landing at specific sites.

C. On-Board Sensing and Perception

For an operational aerobot flight system, a suite of on-board sensors would be used to estimate the vehicle position and velocity with respect to planetary coordinates. It would also estimate the local wind velocity as experienced by the vehicle. The proposed terrestrial flight experiments will use an on-board Global Positioning System (GPS) to emulate some of the planetary aerobot sensors.

The on-board sensor suite to be evaluated includes: 1) a lightweight gyro and accelerometers for dead-reckoning navigation; 2) a sun sensor to determine the angle of the sun with respect to the robot, 3) a gravity vertical sensor, essentially a plumb line, that determines robot orientation with respect to the local vertical; 4) a pressure altimeter for approximate altitude sensing; 5) a compact, lightweight radar altimeter to sense the ground profile at lower altitudes and to provide ground velocity data; 6) a lightweight camera to take images of surface topography for correlation with map data to determine the position of the aerobot with respect to specific target sites; 7) several atmosphere and balloon system temperature and pressure sensors and 8) a solar insolation sensor for real-time measurement of the primary mechanism that adds uncertainty to the balloon lift.

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